A Study on the Twin-Fluid Atomization of a Highly Concentrated Coal-Water Mixture*

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A study has been carried out for the purpose of clarifying spray performances of highly concentrated coal-water mixtures (CWM) and obtaining a guide for the design of practical twin-fluid atomizers. Disintegration mechanisms and spray characteristics were investigated on the simple twin-fluid atomization of CWM, and compared with those of single-phase liquids. Furthermore, these disintegration phenomena and spray characteristics were considered by the proposed disintegration model. In the disintegration of a CWM jet by high-speed air, atomization phenomena are similar to those of low-viscosity liquids. Spray is generated basically by the tearing-off of irregularly shaped small drops from the jet surface and by the splitting-up of the unstably fluctuating jet into spherical drops. With the increase of air velocity, Sauter's mean diameter of spray decreases steeply, but its manner depends on the disintegration mechanism.

**Key Words:** Liquid Atomization, Twin-Fluid Atomizer, Particulate Technology, Spray Combustion, Coal-Water Mixture

1. Introduction

In recent years, coal–water mixture (CWM) fuels have been energetically researched as a substitute fuel for petroleum. Though the atomization quality of CWM is an important factor in determining the spray combustion efficiency, systematic information on atomizing mechanisms and atomization characteristics have been rarely reported because of the complicated properties and flow conditions of CWM.

The present study aims to clarify the basic disintegration mechanism and atomization characteristics of CWM in high-speed air streams by using an externally-mixed twin-fluid atomizer, to verify the reasonability of the proposed liquid disintegration model, and to develop applicable twin-fluid atomizers.

* Received 22nd May, 1987. Paper No. 86-0945A
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Nomenclature

- $\bar{d}_{50}$: Sauter's mean diameter $\mu$m
- $n$: number of spray droplets
- $U_a$: air velocity at a point 5 mm below the nozzle exit m/s
- $W_a$: air mass flow rate g/s
- $W_f$: liquid mass flow rate g/s
- $X$: droplet diameter $\mu$m
- $\mu$: liquid viscosity Pa·s
- $\rho$: liquid density kg/m$^3$
- $\sigma$: surface tension mN/m

2. Experimental Apparatus

The experimental apparatus is schematically shown in Fig. 1. CWM in the reservoir 13 is pressurized and forced out by the rubber bag 12 which is inflated by compressed water, and is supplied to the atomizer. Water in the reservoir 8 is compressed at a constant pressure by nitrogen fed from the bomb 6 through the pressure regulator 7, and the flow rate is adjusted by the needle valve 10 and measured by the capillary orifice flowmeter 9. Atomizing air is compressed by the air compressor 1, and is supplied to the
atomizer 15 through the orifice flowmeter 4 and the needle valve 5.

Figure 2 shows the details of the twin-fluid atomizer used in this study. CWM is supplied into the chamber 1 and is ejected from the nozzle 2 of inner diameter 3 mm. Atomizing air is supplied to the stagnation chamber 4 through an annular slit of width 1 mm. The air velocity $U_a$ measured on the nozzle axis at a point 5 mm below the nozzle edge is adopted as the representative velocity.

Tap water and glycerin are also used in order to compare the peculiarity of the disintegration mechanism of CWM with those of single-phase liquids. Physical properties of these liquids at 20°C are tabulated in Table 1. CWM offered from Ube Kosan Co. Ltd. contains 68.2 wt% of pulverized coal which is ground to 89.5 wt% minus 200-mesh, and large coal particles were filtered off through the 30-mesh screen before experiments. Viscosity is measured 5 minutes after the beginning of rotation of a B-type viscometer at 12 rpm, which will be referred to as the representative viscosity of CWM.

Disintegration phenomena are observed by shadow photography using stroboscope 17 and camera 18. Drop size distribution is measured by the liquid immersion method using a sliding shutter 19. Spray droplets are produced by the different disintegration mechanisms which will be described later, and are generally classified into spherical and shapeless particles according to their shapes. The judgment of particle shape is made by visual observations or drop size measurements. A particle whose difference between the major diameter and the minor diameter is less than 10% of the major diameter is decided as spherical. A particle smaller than 10 $\mu$m is also treated as spherical because of the difficulty of precise judgment. As a representative diameter of a particle, Green's diameter\(^{[15]}\) is adopted.

3. Disintegration Patterns and Mechanisms of a Liquid Jet by High-Speed Air

Figure 3 shows the changes in the disintegration pattern of a CWM jet with increasing air velocity. At low air velocity, the liquid jet vibrates sinuously, and its amplitude and wavelength increase along the jet flow. As air velocity increases, the liquid jet tears off at the trough and the peak of sinuous waves at every half wavelength. As air velocity is increased, the breakup length of the liquid jet becomes shorter than that at low air velocity, the liquid jet becomes slender.

\[ \text{Table 1 Physical properties of liquids} \]

<table>
<thead>
<tr>
<th></th>
<th>$\mu$, Pa·s</th>
<th>$\sigma$, mN/m</th>
<th>$\rho$, kg/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>1.000×10$^{-3}$</td>
<td>72.8</td>
<td>1000</td>
</tr>
<tr>
<td>Glycerin</td>
<td>1.92</td>
<td>63.4</td>
<td>1264</td>
</tr>
<tr>
<td>CWM</td>
<td>2.65</td>
<td>48.3</td>
<td>1260</td>
</tr>
</tbody>
</table>

1987, Vol. 30, No. 269
rapidly below the nozzle exit, and fine spray droplets tear off from the jet surface. The disintegration phenomena of such a droplet generation appear only at high air speed conditions, and small liquid droplets of relatively high coal-particle concentrations are produced by the separation of a large number of coal particles at the aerodynamically-disturbed jet surface. This disintegration mechanism is referred to as the coal separation-wise disintegration(2).

The changes in the disintegration pattern of CWM against the liquid mass flow rate $W_l$ at a high air velocity are shown in Fig. 4. At small $W_l$, the liquid jet diameter decreases rapidly near the nozzle exit, and fine droplets are generated from the liquid surface according to the coal separation-wise disintegration mechanism. As $W_l$ increases, the liquid jet vibrates randomly, becomes unstable, and the coarse droplets are detached according to the unstable jet disintegration mechanism(2). At large $W_l$, the breakup length of the liquid jet increases and the fine droplets tear off from the liquid surface according to the coal separation-wise disintegration. At the tip of the jet, the liquid lump is generated by the jet instability.

More detailed disintegration phenomena are shown in Fig.5 with magnified photographs. In order to compare the disintegration mechanism of CWM with other single-phase liquids, the disintegration phenomena of high-viscosity glycerin and water are shown in Fig. 6 and Fig. 7, respectively. In Fig. 5 small irregularities appear on the liquid surface at small $U_a$, but no fine droplets tear off from the surface. These irregularities will be generated as follows. When the agglomerate structure of coal particles in CWM is broken up by the shear stress of air, and the gap between particles is widened, the surrounding water flows into the widened gap, which results in the reduction of water concentration at the jet surface and the projection of coal particles from the surface. At large $U_a$, spray droplets are produced by the coal separation-wise disintegration from the jet surface and by the detaching of liquid lumps at the tip of the unstable liquid jet. With increasing $U_a$, the jet breakup length decreases, the former disintegration becomes superior to the latter one, and spray of small diameter is obtained.

By comparing the disintegration phenomena of CWM with that of glycerin whose viscosity is similar to the representative viscosity of CWM (see Fig. 6), it is noted that fine liquid ligaments cannot be stretched from the jet surface in the case of CWM at high air velocity. On the other hand, in the case of glycerin, the liquid jet remains stable, even though it is accelerated and stretched by the shear stress of air. The discrepancy of disintegration phenomena between these liquids will be explained as follows. Viscosity of CWM is determined by the size of coal particles, their agglomeration states, and the dispersion states of water and added agents in CWM. Though the representative viscosity of CWM is as high as glycerin, when the agglomerate structure is broken once by the shear stress of air and the surrounding water flows into the widened gap between particles, the actual viscosity decreases abruptly and becomes almost equivalent to that of water.
In Fig. 7, which shows the disintegration phenomena of water, relatively large drops are generated at low air velocity. In the case of CWM, fine droplets are also included in the spray, even at the condition when the coal separation-wise disintegration takes place. The disintegration of water occurs mainly according to the growth of disturbances on the liquid surface, and wavelengths of these disturbances are inversely proportional to the second power of the air velocity. As air velocity decreases, disturbance wavelength increases rapidly, consequently, large droplets are produced by the disintegration of a liquid jet, while the wavelengths of disturbances on the liquid surface of CWM are dependent on the scale of coal particles or their agglomeration states. At small \( U_a \), the force that amplifies the disturbances by fluctuations of pressure acting on the surface is smaller than that by the surface tension that suppresses the growth of disturbances, so the liquid column is stable and the coal separation-wise disintegration cannot take place. However, with increasing \( U_a \), the coal separation-wise disintegration begins to occur, the wavelengths of disturbances decrease rapidly, and fine droplets are produced from the liquid surface. If \( U_a \) increases further, the disintegration phenomena of CWM become similar to those of water due to the reason mentioned above.

4. Drop Size Distributions and Sauter's Mean Diameters of Spray

Figure 8 shows the change in spray droplet shapes of CWM by air velocity. The spray consists of spherical liquid particles and shapeless particles. A spherical particle is regarded as containing relatively high concentrations of water, and shapeless particle containing low concentrations of water. As the air velocity increases, the spherical particles become smaller and the number of small shapeless particles increases sharply. The cumulative volume fraction of CWM spray which is normalized by the volume of total spray droplets are shown in Fig. 9 and Fig. 10. As the volume of a shapeless liquid particle is assumed to be equal to that of a sphere of Green's diameter, in calculations, the actual cumulative volume fraction of shapeless particles will be generally less than the

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**Fig. 7** Disintegration phenomena of water

**Fig. 8** Change of spray droplet shapes of CWM by air velocity

**Fig. 9** Cumulative volume fractions of CWM spray at low air velocity

**Fig. 10** Cumulative volume fractions of CWM spray at high air velocity
value shown in the figures. It is noted that the maximum diameter of spherical particles decreases rapidly with increasing air velocity, and the cumulative volume fraction of shapeless particles increases without the noticeable decrease of the maximum diameter.

Figure 11 compares the change of the cumulative volume fraction by air velocity with that of pulverized coal contained in CWM. With an increase of $U_a$, the maximum diameter of CWM decreases, and the distribution of cumulative volume fractions of CWM approaches that of pulverized coal.

Figure 12 shows the change of the volume ratio of shapeless particles to total spray particles against air velocity. With an increase of $U_a$, the volume ratio increases and reaches almost a constant value at $U_a > 250$ m/s, but is scarcely influenced by the liquid flow rate, because the coal separation-wise disintegration is remarkably influenced by air velocity, but is independent of $W_l$.

There are some reports on twin-fluid atomizations of CWM and their drop size distributions. Sakai et al. assumed the disintegration model of CWM that coal particles are contained in liquid droplets randomly, uniformly and independently of drop size, and calculated the drop size distribution, and then verified the reasonability of this model by atomization experiments of low concentrations of CWM and coal-oil mixture (COM). In this report, the drop size distribution calculated by applying their model and the proposed equation was compared with experimental data. The results are shown in Fig. 13 and Fig. 14. In the figures, the broken line shows the drop size distribution for water, the chain-dot line shows the predicted distribution from the model and the solid line shows the experimental data.

In the case of low air velocity (see Fig. 13), the predicted distribution agrees well with the experimental data. At high air velocity (see Fig. 14), the mode diameter and its size frequency of experimental distribution are smaller and higher than those of the predicted distribution. In particular, the result of the predicted distribution differs from the experiment. In the case that $U_a$ is small and the coal separation-wise disintegration is not active, the proposed model roughly fits this experimental situation because a large number of spherical particles are included in the

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**Fig. 11** Change of cumulative volume fraction by air velocity

**Fig. 12** Change of volume ratio of shapeless particles by air velocity

**Fig. 13** Comparison of predicted drop size distribution with experiment at low air velocity

**Fig. 14** Comparison of predicted drop size distribution with experiment at high air velocity
spray, and the predicted distribution agrees well with experimental data. However, at high air velocity, the assumption that coal particles are included uniformly in each spray droplet becomes unsuitable for the experimental situation owing to the increase of fine shapeless particles. In the case of highly concentrated CWM, it will be necessary to develop this model into a new one that considers the disintegration mechanism.

Figure 15 shows the change of Sauter's mean diameter by the air velocity for various flow rates. At present, the assessment method and the simple measurement method of shapeless particle sizes have not been established, so in this report a shapeless particle is conveniently treated as a sphere of Green's diameter when manifesting spray characteristics.

As the air velocity increases, Sauter's mean diameter initially decreases rapidly, changes gradually as the air velocity approaches 250 m/s, and then decreases rapidly again. It will be presumed from the change of drop size distribution and the result indicated in Fig. 12 that small shapeless particles produced by destruction of weak agglomerate structures of CWM increase first with increasing air velocity, approach a saturated disintegration state at about $U_a = 250$ m/s, and when the air velocity exceeds 250 m/s, shapeless particles in the air stream begin to break up with the destruction of stronger agglomerate structures by the intense shear stress of air. However, more detailed discussions are necessary for clarifying this mechanism.

Sauter's mean diameter has a tendency to increase with increasing liquid flow rate. As shown in Fig. 12, the volume ratio of shapeless particles in spray is not influenced by a liquid flow rate. It is thus considered that the drop sizes of spherical and shapeless particles also change with liquid flow rate, resulting in constant volume ratios.

5. Conclusions

In order to verify the reasonability of the disintegration mechanisms proposed and to obtain a guide for the design of practical twin-fluid atomizers, the disintegration mechanism and spray characteristics were investigated using a simple twin-fluid atomizer, and the following results were obtained.

(1) Spray is produced based on the coal separation wise disintegration mechanism at the liquid jet surface and the unstable jet disintegration mechanism. Shapeless particles are mainly produced by the former mechanism and spherical particles are produced by the latter one.

(2) As air velocity increases, the disintegration phenomena becomes similar to that of water because the higher the shear rate is, the lower the dominant viscosity of CWM becomes, and it approaches that of water during the breaking-up of agglomerate structures.

(3) Small shapeless particles increase with the increase of air velocity, and the drop size distribution of total spray droplets approaches that of pulverized coal included in CWM.

(4) Under the injection condition that air velocity is low and the unstable jet disintegration mechanism is dominant over the disintegration phenomena, the predicted drop size distribution calculated from the model in which coal particles of different size are randomly and uniformly distributed in each spray droplet agrees with experimental data. However, this model becomes unsuitable at high air velocities because of the increase of shapeless particles in spray.

(5) With the increase of air velocity, the change of Sauter's mean diameter shows two different tendencies corresponding to the destruction mode of agglomerate structures of coal particles.

Acknowledgments

The authors would like to thank the staff of their laboratory, in particular, Messrs. M. Umehara, M. P. Chiba and T. Watanabe, for their valuable advise and experimental assistance. The authors also wish to express their appreciation to Ube Kosan Co. Ltd. and Takuma Co. Ltd. for the provision of CWM. This work has been financially supported in part by Grant-in-Aid for Scientific Research of the Ministry of Education, Science and Culture of Japan.
References